

# **BNL Nuclear Theory Update**

- Recent highlights and plans
- Synergies and collaboration between  
Lattice QCD and HI collision modeling
- Budget and staffing

**DOE one-day site visit, July 23, 2015**

# Nuclear Theory Group (NTG)

## Long term Scientific Staff:

B. Schenke  
D. Kharzeev (joint with Stony Brook)  
L. McLerran  
R. Pisarski  
J. Qiu (Group Leader since July, 2015)  
**M. Stratmann (Tübingen, from April, 2014)**  
R. Venugopalan (Group Leader, 2010-2015)

## Post-doctoral Fellows:

S. Schlichting (Goldhaber Fellow)  
M. Sievert (BSA EIC PDF)  
P. Tribedy (1/3-2/3 joint with STAR)  
Y. Yin

## Other Staff

A.J. Baltz (Emeritus)

## Group Administrator:

D. Davis

# Lattice Gauge Theory Group (LGT)

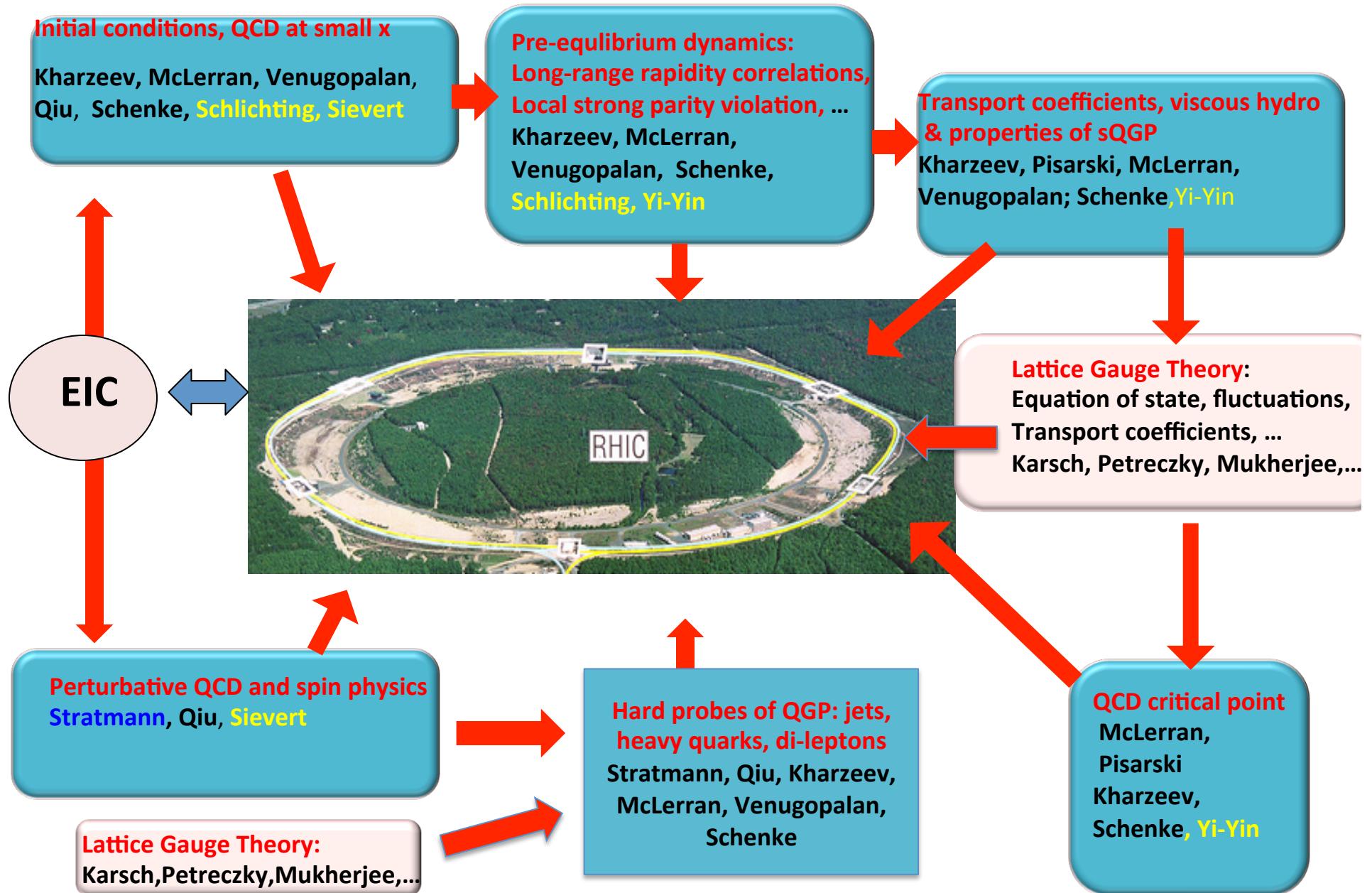
## Long term Scientific Staff:

F. Karsch (Group Leader, joint with Bielefeld)  
P. Petreczky  
S. Mukherjee

## Post-doctoral Fellows:

S. Sharma  
H. Ohno (on leave from Tsukuba)  
**Group Administrator:**  
N. Kelly

# Nuclear Theory @ BNL & the physics of RHIC



## **Recent highlights and plans (since 2014 DOE S&T review)**

# A quick summary of recent activity

## Productivity (20 month period, Oct.2013-May 2015):

Papers: NTG, 69 refereed including 15 letters; LGT: 12 (2014-15) incl. 3 letters

Invited Talks – NTG, 131 invited talks, colloquia, seminars; LGT: 21 invited talks

Numerous meetings organized, IAC representation

## NSAC Long-Range Planning process:

QCD Town meeting plenary presentations (Mukherjee, Qiu, Petreczky, Schenke)

Program Committee (Hot QCD, Karsch, Venugopalan; Cold QCD, Qiu)

Major Whitepaper contributions (Karsch, Petreczky, Qiu, Venugopalan)

Resolution Committee (NSAC LRPWG, Venugopalan)

## Topical Collaboration in Nuclear Theory (DOE LAB 15-1269):

BEST Collaboration – BES (Mukherjee – PI, Kharzeev, Schenke, Venugopalan, ...)

TMD Collaboration – 3D imaging (Qiu – PI/Co-SP, Venugopalan)

Heavy Flavor in Hot QCD Matter Collaboration – (Petreczky)

QURHIC Collaboration – HI theory/data comparison (Schenke, Venugopalan)

## Computing Grants:

NP SciDAC-3 Grant (Karsch, PI); ASCR grant on TITAN (Mukherjee, PI);

NERSC Exascale software support grant (co-PI, Karsch)

## Awards and Honors (2013-present)

D. Kharzeev: Humboldt Award (2013), Severo Ochoa Prof., Madrid (2014)

L. McLerran: 2015 APS Feshbach Prize in Theoretical Nuclear Physics

B. Schenke: DOE Early Career Award (2014)

R. Venugopalan: Research Excellence Prof. Award Heidelberg (2014-16),  
EMMI Professorship (2014)

Group research featured in Science, Physics World, Scientific American, DOE Office  
of Science Highlights, PRL Editors Suggestion,...

## Other synergistic activities

Karsch: BNL BlueGene/Q Program Committee, Exec. Comm. USQCD

Kharzeev: DNP Nomination Committee, Director, Center for Quantum Materials, SBU

McLerran: Chair HIC for FAIR Committee, Prog. Committee EMMI

Qiu: ePHENIX LOI Review Panel, MSU-FRIB lattice advisory committee

Pisarski: Deputy Director RBRC, member BNL Council

Petreczky: Chair, APS Group on Hadron Physics

Schenke: Past Convener, JET Coll. Monte Carlo Working Group

Venugopalan: NAC, INT Seattle (2015-17), NSAC (2012-16) & LRP Working Group,  
Chair line APS GHP (2014-17), NSF Panel Expt. Nucl. Phys.

*Group members serve on numerous Conference International Advisory Committees*

Karsch, Kharzeev, McLerran, Pisarski and Venugopalan, Editors respectively of Eur. J. Phys. C, Int.J.Mod.Phys,NPA, PRD, Annals of Physics

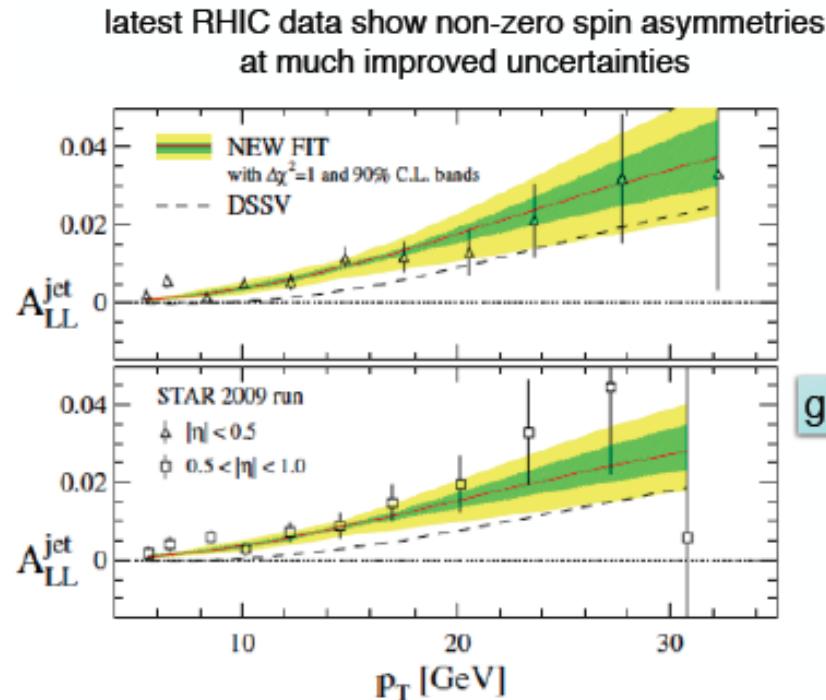
# Global QCD analysis of helicity PDFs - $\Delta G$

- How does quark-gluon dynamics generate the proton spin ?

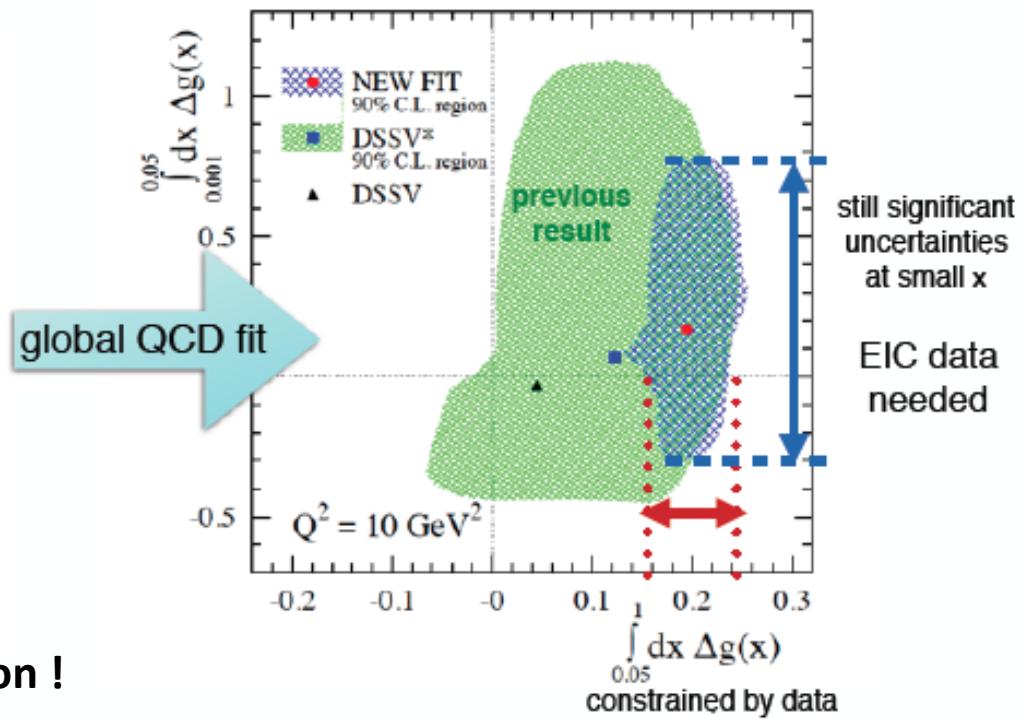
$$S(\mu) = \sum_r \langle P, S | \hat{J}_f^z(\mu) | P, S \rangle = \frac{1}{2} \equiv J_q(\mu) + J_g(\mu) = \frac{1}{2} \Delta \Sigma(\mu) + L_q(\mu) + \Delta G(\mu) + L_g(\mu)$$

D. de Florian, R. Sassot, M. Stratmann, W. Vogelsang, PRL 113 (2014) 012001

results featured in Sci. Am., Phys. World, .

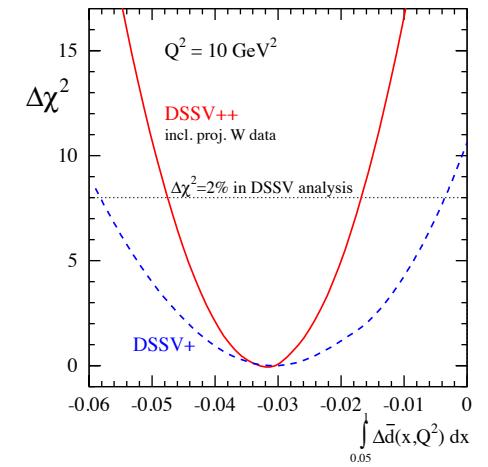
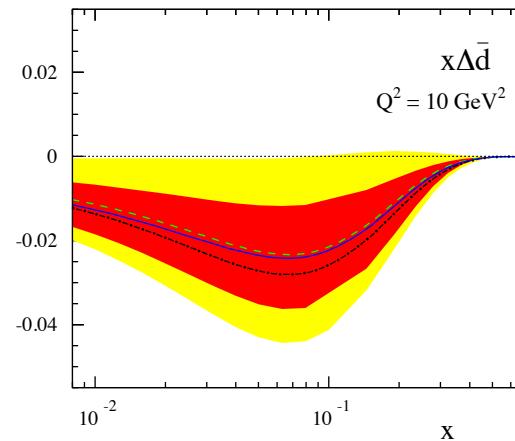
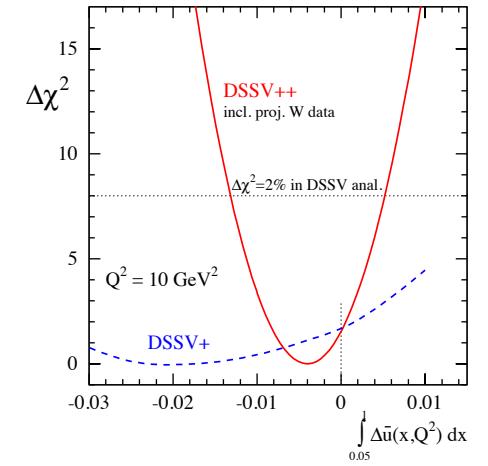
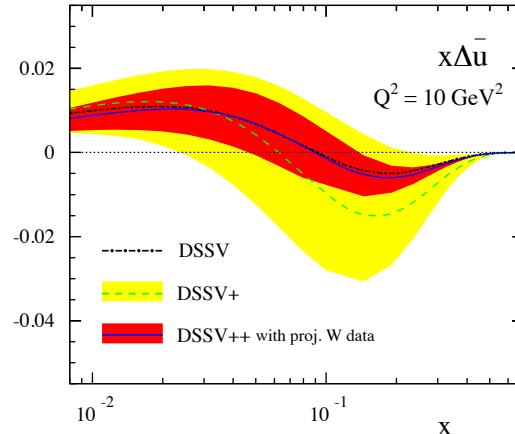
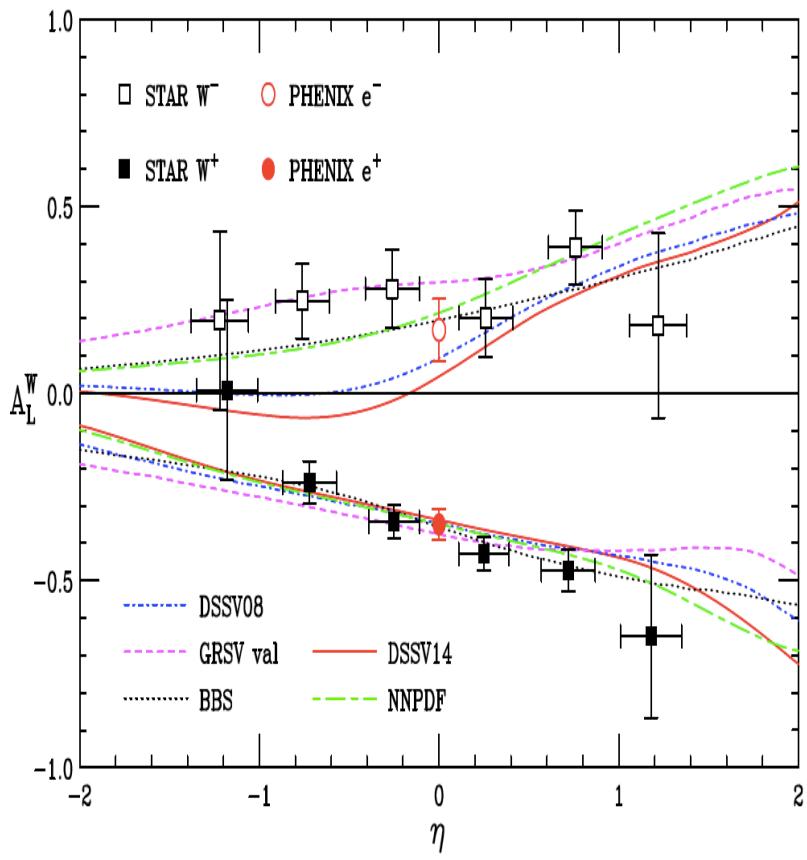


◆ Clear evidence for gluon polarization !  
Constrains orbital angular momentum



# Global QCD analysis of helicity PDFs – Sea

M. Stratmann, arXiv:1304.0079



- ❖ Quarks: ~ 30% of proton spin
- ❖ Gluons: ~ 40% (?) of proton spin

The rest?

Stratmann's work has huge impact on analysis and interpretation of RHIC spin experiments (DSSV has 231 citations)

# Transverse Spin: Sign change & Evolution

RHIC spin milestone

□ TMD factorization – Probe confined transverse motion in proton:

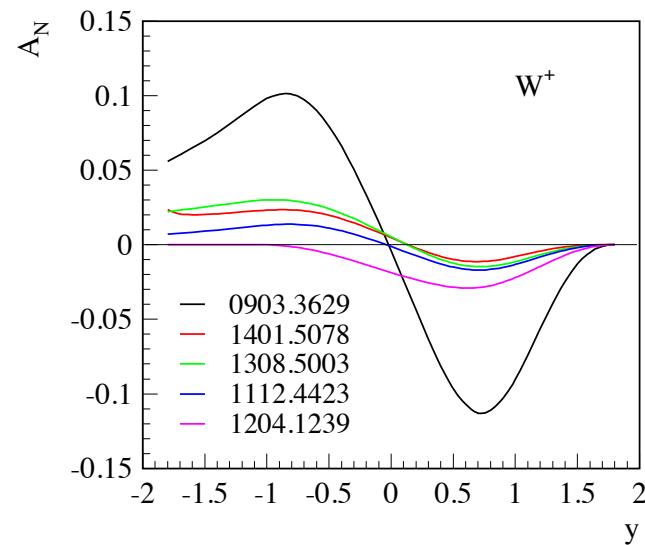
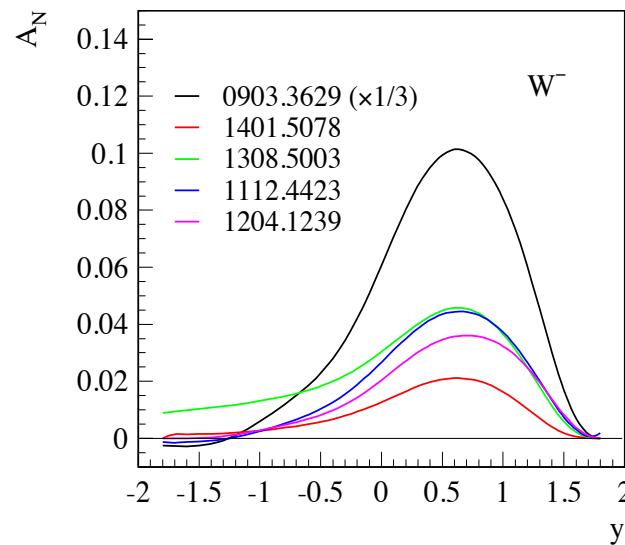
Sivers Effect: hadron spin vs. preference of parton motion

Prediction: Sivers function from DIS = – Sivers function from DY, W/Z, ...

TMDs in nuclei, probing saturation with spin Kovchegov, Sievert, 1505.01176

□ Current prediction and uncertainty of QCD evolution:

Qiu et al.



TMD collaboration proposal: Lattice, theory & Phenomenology  
RHIC is a unique facility to test this (W/Z – DY)!

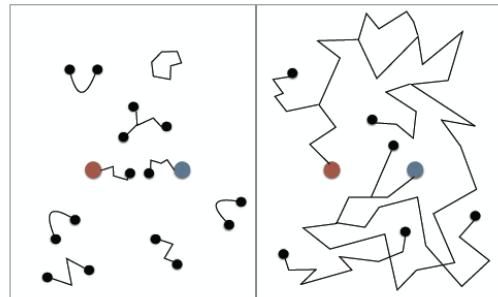
# Heavy quarkonium production

- 1<sup>st</sup> proof of QCD factorization:  
pQCD factorization valid to all powers  
In  $\alpha_s$  and to leading and NLO pow  
in  $1/p_T$  but not beyond!

- CGC & NLO pQCD +NRQCD framework

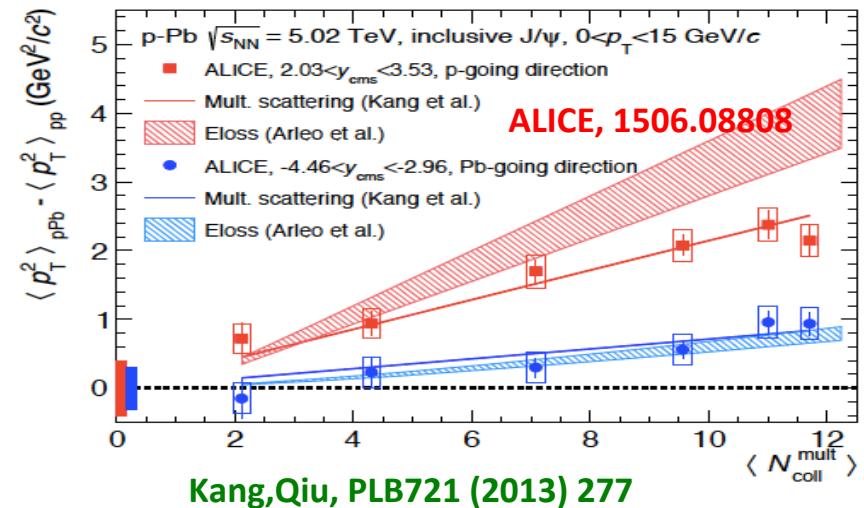
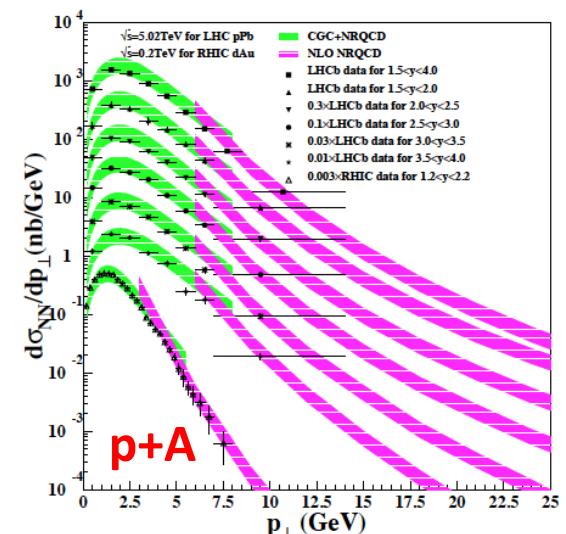
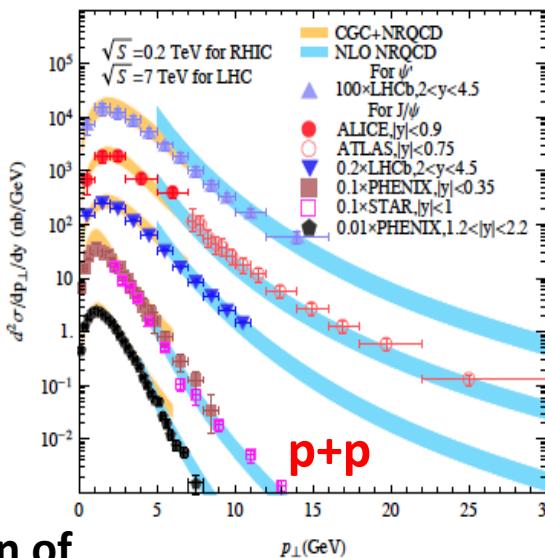
Kang,Ma,Venugopalan,JHEP 1401 (2014)  
 Ma, Venugopalan, PRL 113 (2014) 19, 192301  
 Ma, Venugopalan, Zhang, 1503.07772  
 See also, Qiu,Sun,Xiao,Yuan, PRD89 (2014)

- Entropic dissociation as explanation of A+A RHIC vs LHC J/ $\psi$  suppression puzzle



Kharzeev,PRD90 (2014) 7,074007  
 Hashimoto,Kharzeev, PRD90 (2014) 12, 125012

Kang, Qiu and Sterman, PRL108,( 2012)  
 Ma, Qiu, Zhang, PRD89 (2014), 094029, 094030  
 Kang, Ma, Qiu, Sterman, PRD90 (2014) 034006  
 Ma, Qiu, Sterman, Zhang, PRL113 (2014) 14, 142002

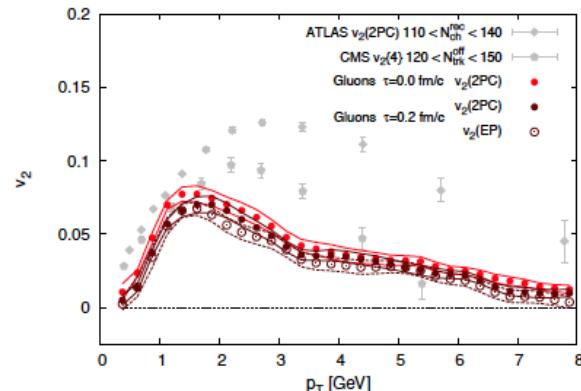


Kang,Qiu, PLB721 (2013) 277

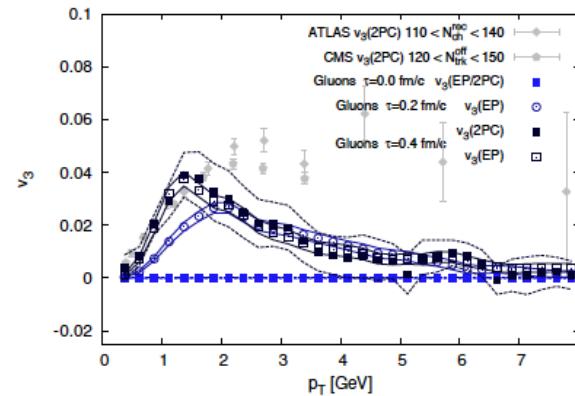
# Collectivity in small systems: the p+A puzzle

□ Is the ridge an initial state effect?

Glasma Yang-Mills dynamics describes  $v_2$  &  $v_3$  in p+A @ LHC



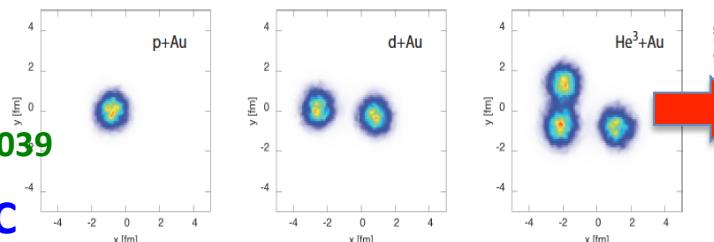
Schenke, Schlichting, Venugopalan, PLB747 (2015) 76



Collectivity arises due to  
initial state correlations within  
domains of color charge  
Dumitru, McLellan, Skokov, PLB743 (2015) 134

□ Or is it a final state effect?

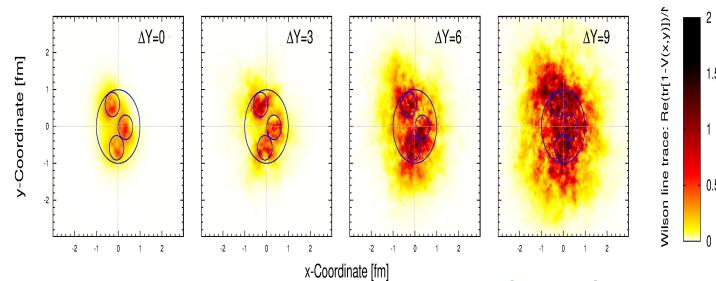
Schenke, Venugopalan, NPA931 (2014) 1039



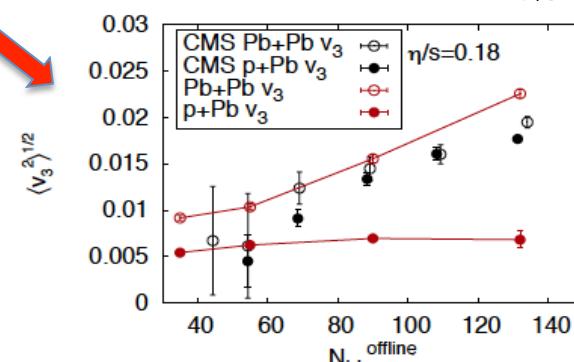
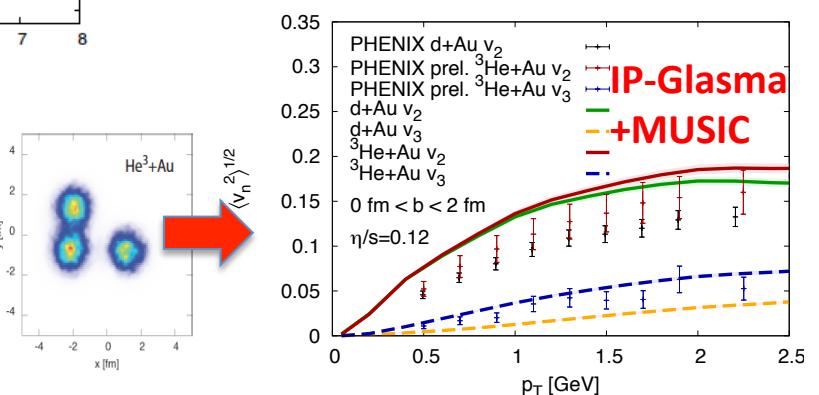
Works for d+A & <sup>3</sup>He+A at RHIC

However, IP-Glasma+MUSIC fails with LHC p+A data...

Sensitivity to initial shape?



Schenke, Schlichting, PLB739 (2014) 313



Schenke, Venugopalan, PRL113 (2014) 102301

# Thermalization rises to the fore

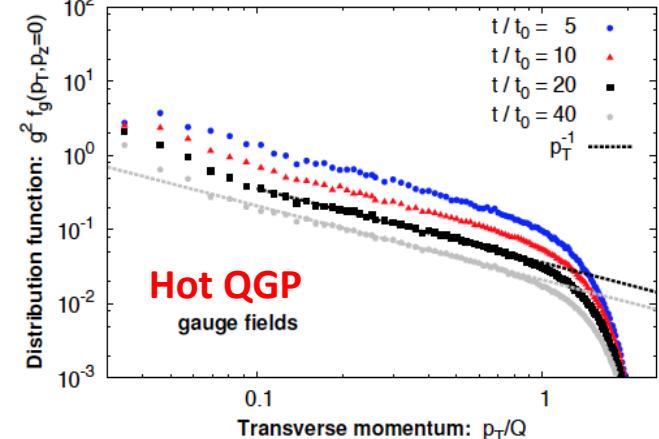
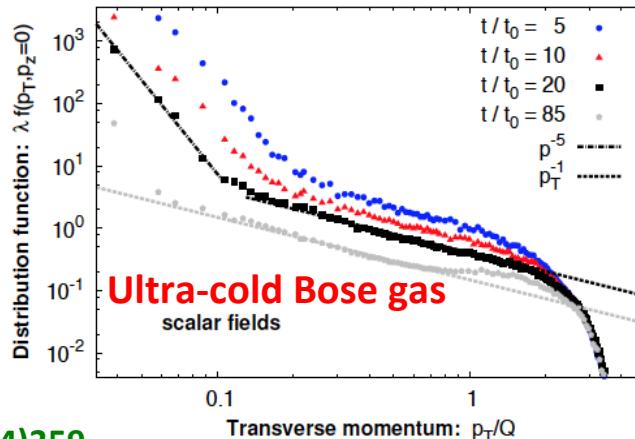
- The world's hottest matter and its coldest thermalize the same way...

Does this universality hint at Bose Condensation In HI collisions?

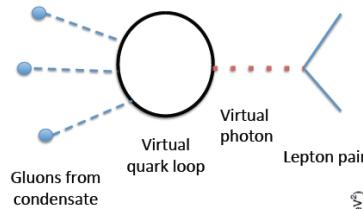
Blaizot,Gelis,Liao,McLerran,  
Venugopalan,NPA873 (2012)68

Blaizot,Liao,McLerran,NPA931 (2014)359

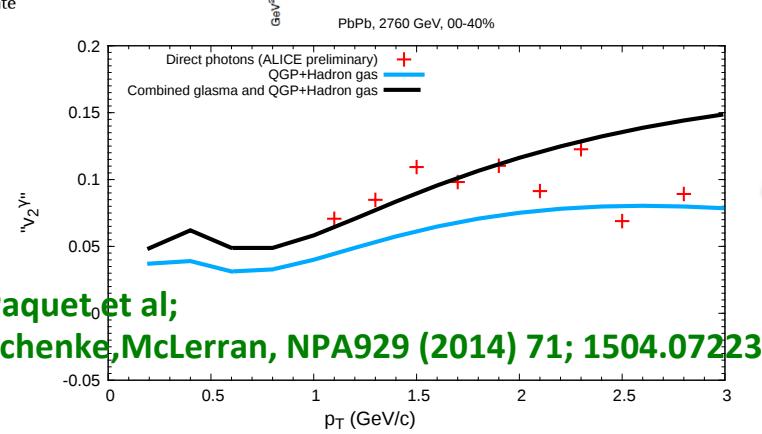
Berges,Boguslavski,Schlichting,Venugopalan,  
PRL114 (2015) 6, 061601, PRL Editors Suggestion



- Electromagnetic probes excellent signature of space-time history of HI collisions

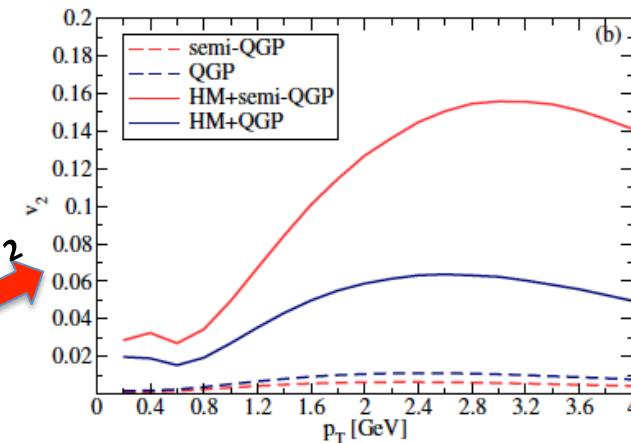


McLerran et al., NPA900 (2013)16



Paquet et al;  
Schenke, McLerran, NPA929 (2014) 71; 1504.07223

Photon  $v_2$

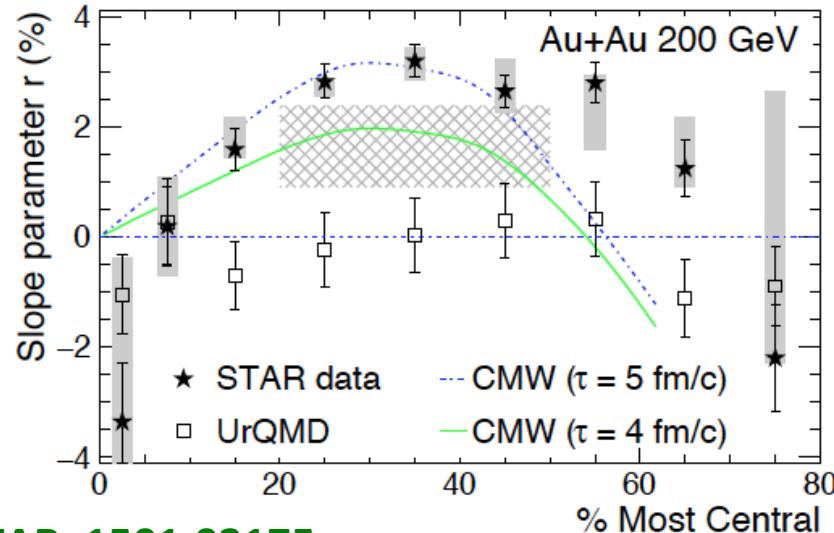
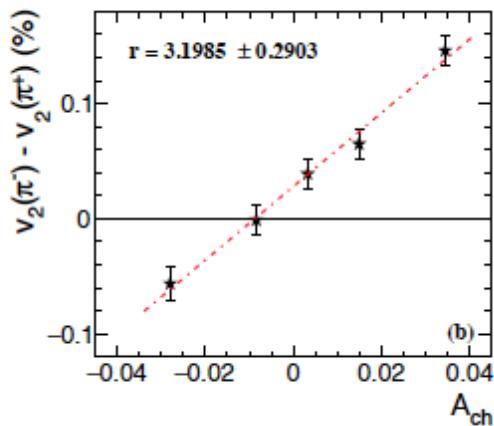


Alternative explanation, emission  
from semi-QGP Pisarski et al., PRL114 (2015) 072301,  
Hidaka, Pisarski, 1504.01770, Lin, Pisarski, PLB730 (2014) 236

# Quantum anomalies in extreme conditions



CMW: electric charge separation induced by topological transitions in external B field  
 CSE: chiral charge separation along external B field at finite baryon density



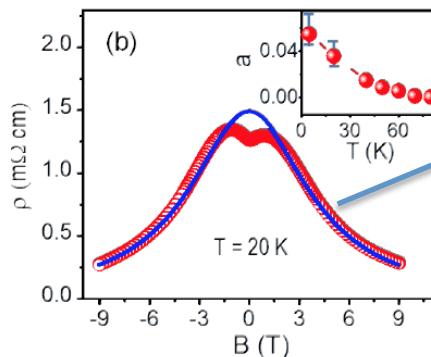
## Evidence for Chiral Magnetic Wave? STAR, 1501.02175

At  $\sqrt{s_{NN}} = 200$  GeV, the slope of the difference of  $v_2$  between  $\pi^-$  and  $\pi^+$  as a function of  $A_{ch}$  exhibits a centrality dependence, which is qualitatively similar to calculations that incorporate a chiral magnetic wave effect. Similar centrality dependence is also observed at lower energies.

Y. Burnier, D. Kharzeev, J. Liao, H-U. Yee,  
 Phys. Rev. Lett. 107 (2011)052303

## Chiral Magnetic Effect in ZrTe<sub>5</sub>

ARPES experiments at BNL find qualitative evidence for CME



Blue curve (CME estimate)  
 compared to Magneto-resistance  
 ss function of B field

# **Synergy and collaboration between Lattice QCD and HI collision modeling**

# Building blocks of hydro modeling

- Other aspects such as jets and Onia: I will focus on aspects of LGT-NTG synergy on the QCD phase diagram

3+1D viscous relativistic fluid dynamics

Realistic fluctuating initial state with distributions of all conserved charges

Equation of state at finite baryon density

$\delta f$  corrections at finite baryon density

Microscopic description of hadronic stage

# EOS for 2+1-flavor QCD at finite $\mu_B/T$

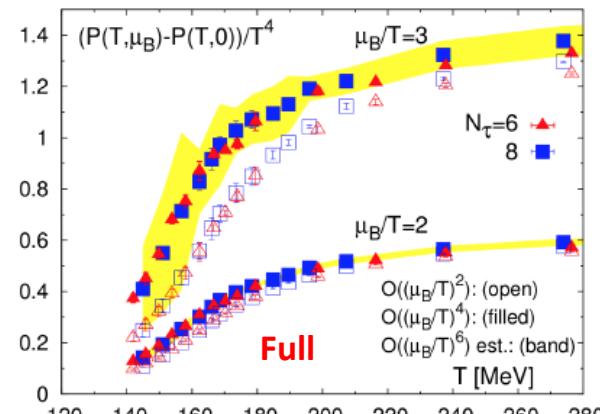
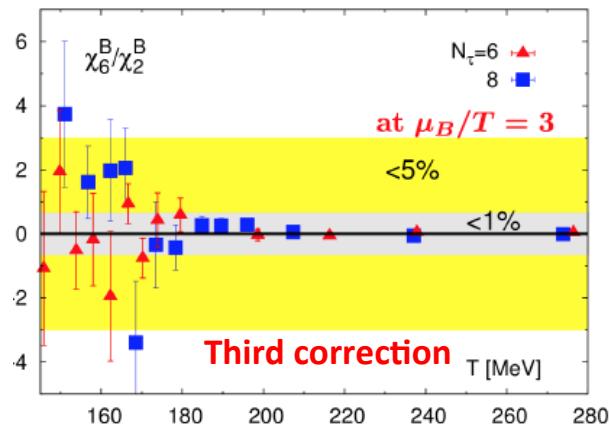
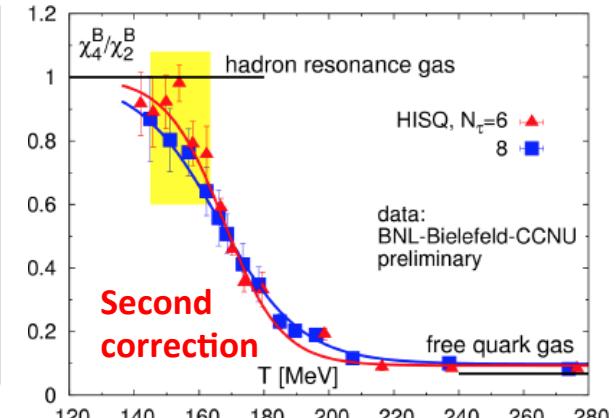
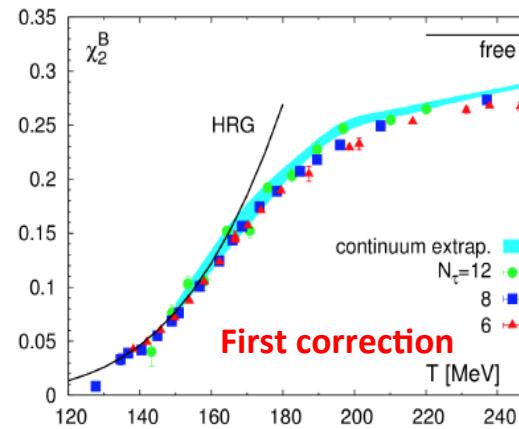
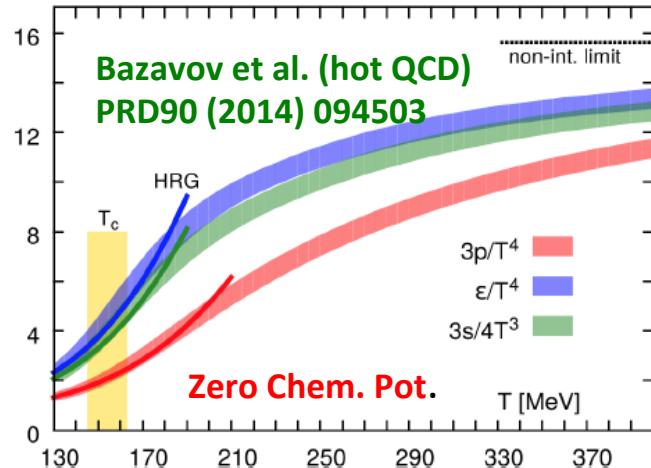
$$\frac{\Delta(T, \mu_B)}{T^4} = \frac{P(T, \mu_B) - P(T, 0)}{T^4} = \frac{\chi_2^B}{2} \left( \frac{\mu_B}{T} \right)^2 \left( 1 + \frac{1}{12} \frac{\chi_4^B}{\chi_2^B} \left( \frac{\mu_B}{T} \right)^2 \right)$$

+  $\frac{1}{720} \frac{\chi_6^B}{\chi_2^B} \left( \frac{\mu_B}{T} \right)^4$



LGT,Karsch et al.

estimating the  $\mathcal{O}((\mu_B/T)^6)$  correction:

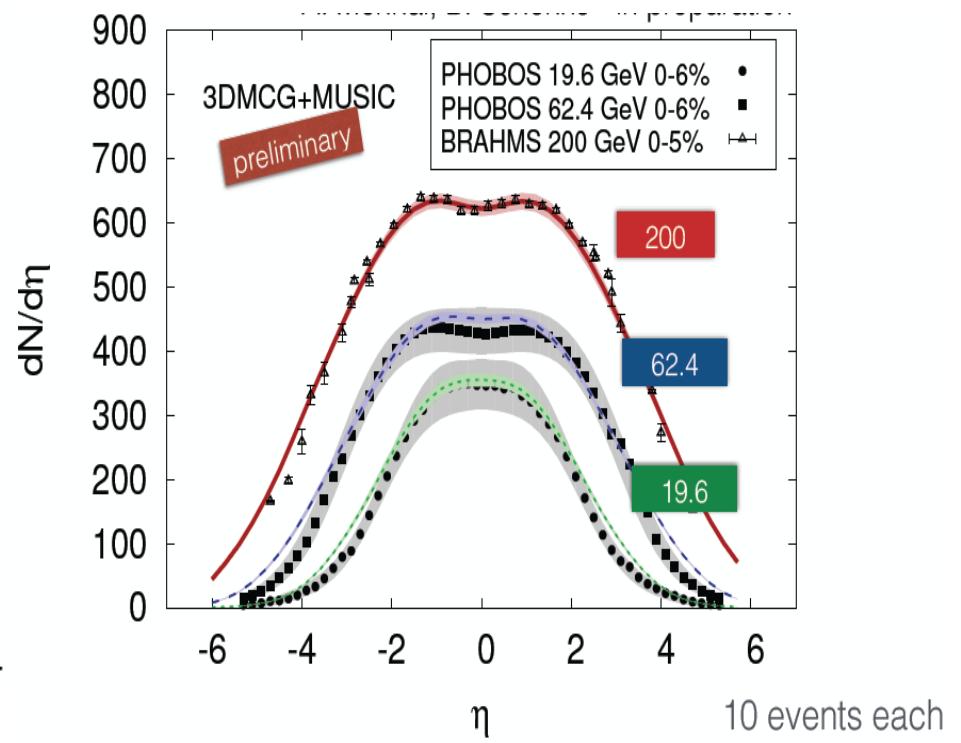
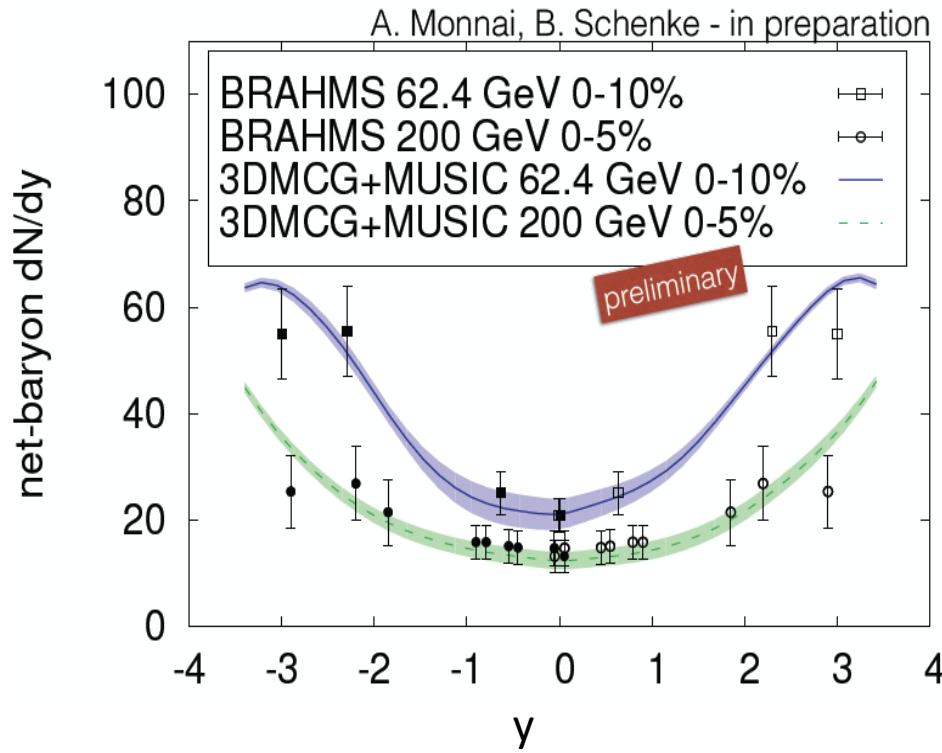


**EOS absolutely critical for hydrodynamical modeling**

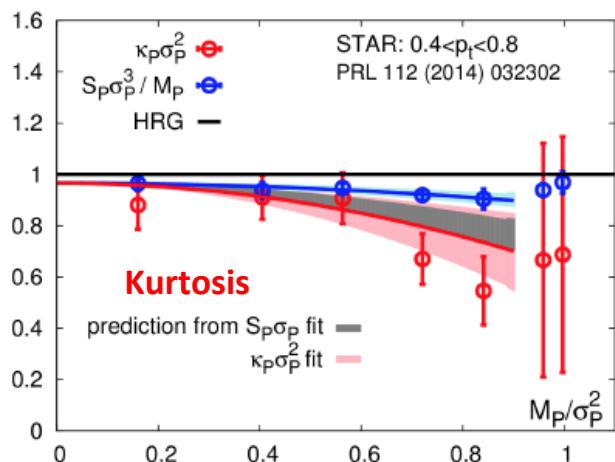
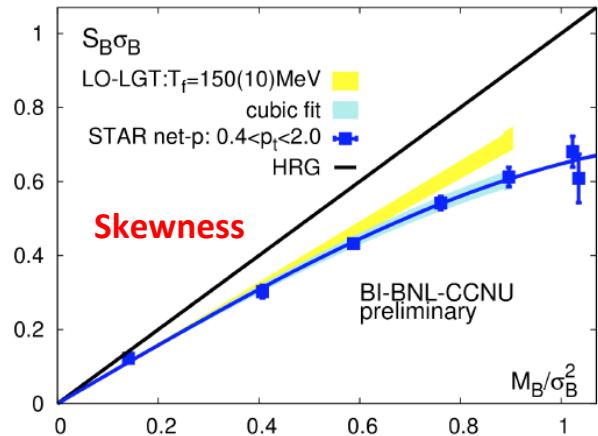


The EoS is well controlled for  $\mu_B/T \leq 2$

# Hydro results



# Conserved charge fluctuations



$$S_B \sigma_B = \frac{\chi_4^B}{\chi_2^B} \frac{M_B}{\sigma_B^2} + \frac{1}{6} \left( \frac{\chi_6^B}{\chi_2^B} - \left( \frac{\chi_4^B}{\chi_2^B} \right)^2 \right) \left( \frac{M_B}{\sigma_B^2} \right)^3 + \dots$$

**LQCD prediction:**  $\frac{\chi_6^B}{\chi_2^B} < 0.64$

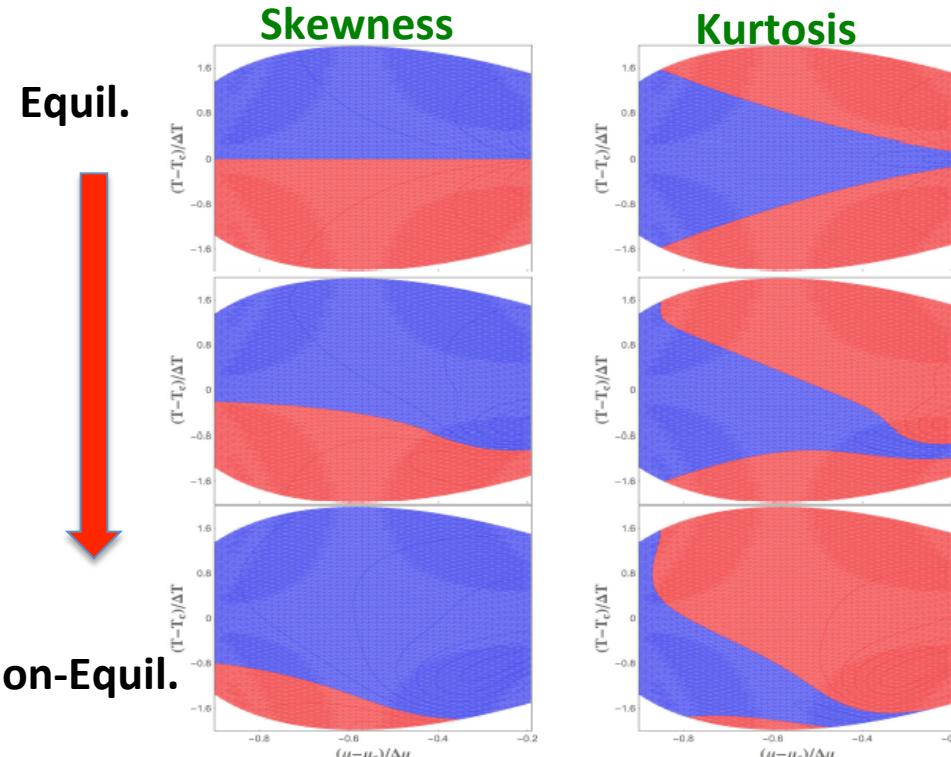
**STAR estimate:**  $\frac{\chi_6^P}{\chi_2^P} \simeq 0.50(15)$  at  $\sqrt{s} = 200$  GeV

$$\kappa_B \sigma_B^2 - \frac{S_B \sigma_B^3}{M_B} = \frac{1}{3} \left( \frac{\chi_6^B}{\chi_2^B} - \left( \frac{\chi_4^B}{\chi_2^B} \right)^2 \right) \left( \frac{M_B}{\sigma_B^2} \right)^2$$

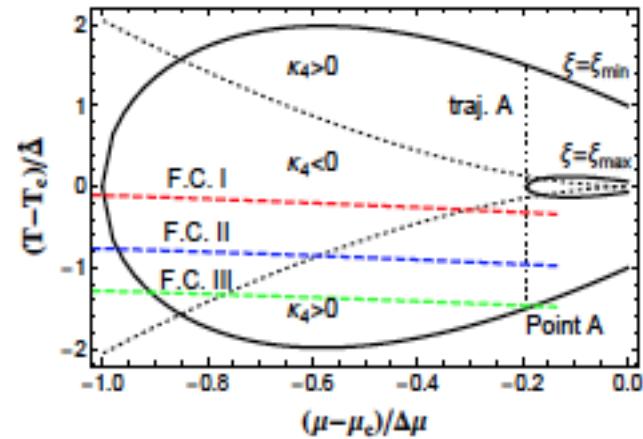
**Claim:** in c.m. energy range of 20-200 GeV, patterns of up to 4<sup>th</sup> order cumulants of electric charge and proton # can be understood in terms of QCD equil. thermodynamics; ratios of electric charge cumulants determine freeze-out  $T-\mu_B$

- This may be good news for hydrodynamic simulations of the beam energy scan -- for quantitative comparisons of lattice with data...

# Conserved charge fluctuations



Mukherjee,Venugopalan,Yin, arXiv:1506.00645



Memory effects can differ in magnitude and sign from equilibrium expectations

- On the other hand, more sophisticated modeling of non-equilibrium effects may be essential for data-theory comparison ...

The Beam-Energy Scan Topical Collaboration will combine community resources in lattice,dynamical modeling and experiment, in mapping out a large region in the QCD phase diagram (**S. Mukherjee, PI, strong representation and synergy between BNL LGT and NTG**)

# **Budget and staffing**

# Budget Challenges

**NTG+LGT Budget:**

**Short of ~ 3.5 FTEs – a long term problem in the NTG+LGT Groups**

**Shortfall thus far made up by Physics Dept. and Operations funds**

**Staffing: Replacement of M. Stratmann:**

**Recommended by 2014 S&T review**

**Critical for the program (Spin, EIC, sPHENIX ...)**

**Short-term solution:**

**RBRC Fellow – ½ salary for 5 yrs**

**Potential of Early Career Award for an outstanding candidate**

**Long-term solutions:**

**Active On-going discussions for a long-term solution; Group demographics are healthy and favor an orderly solution while maintaining Group record of excellence**

# Summary

- ❖ The BNL Nuclear Theory Group is a World Leader in High Energy Nuclear Physics  
**(NTG+LGT very highly rated in 2013 DOE Comp. Review and in  
very favorable September 2014 DOE S&T review )**
- ❖ Vigorous research program aimed at understanding fundamental structure of matter – strongly tied to goals of RHIC facility
- ❖ Synergy with research done by experimental groups, RBRC, Lattice Gauge Theory, High Energy , Condensed Matter, Stony Brook NT
- ❖ Initiatives to develop and solidify science case for RHIC II and EIC  
**Replacement of Stratmann essential to maintain world leading efforts in RHIC spin, EIC polarized e+p, jets with sPHENIX physics and, with other targeted hires, the successful evolution of the group in the next decade**

# **Back-up slides**

# Recent departures

## Post-docs:

V. Skokov (left Sept.2013, Asst. Prof. at W. Michigan U.)

Y. Q. Ma (left August 2014, Junior faculty at Peking University)

M. Hentschinski (departs Sept. 30, 2014, post-doc at UNAM, Mexico)

Lattice personnels ...

## Staff:

J. Millener (retired, 2013)

M. Stratmann (at Tübingen, from April 2014)

## Students:

H. Zhang (post-doc at Ohio State U, Sept.2014)

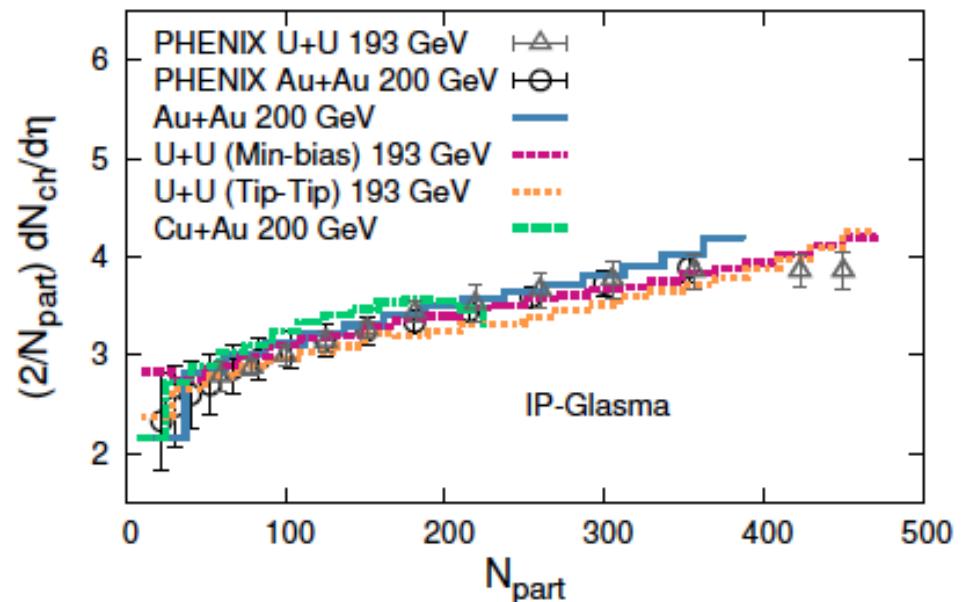
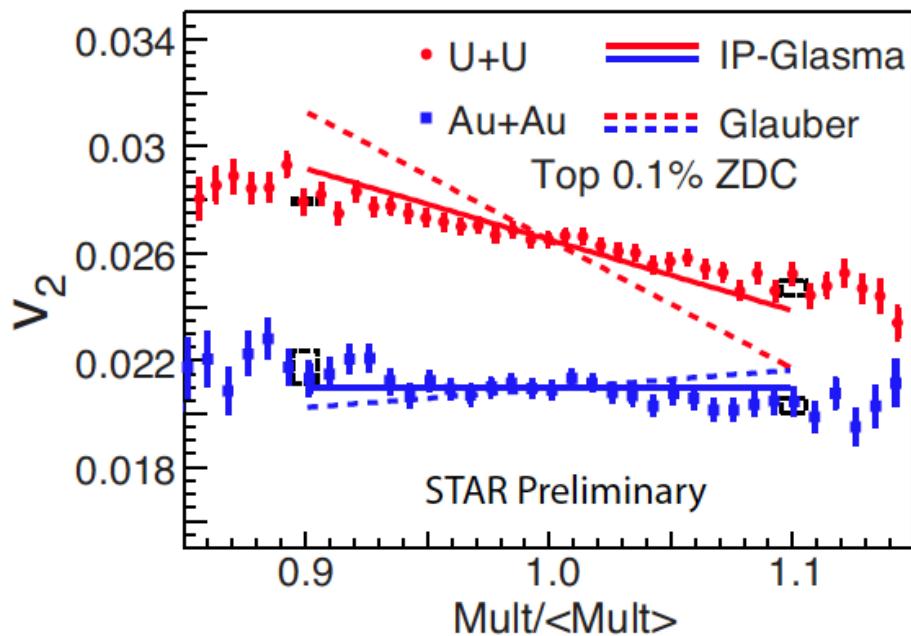
F. Loshaj (post-doc at Karlsruhe U., Fall 2014)

# From Glasma to hydrodynamic flow

## □ U+U and Cu+Au collisions at RHIC

Theory: Schenke,Tribedy,Venugopalan, PRC89 (2014), Editor's pick

Data: STAR, H. Wang, NPA 2014, in press



◆ *Prediction in good agreement with experiment*

Recent work by Schenke and collaborators on improving description of ultra-central events by including nucleon correlation effects

# EIC Science case

NTG group members play a leadership role in establishing the science case for a future EIC

- ❑ Joint BNL/Jlab EIC whitepaper

Qiu was co-editor of the Joint BNL/JLab whitepaper on EIC science (arXiv:1212.1701)  
Stratmann and Venugopalan were co-authors

- ❑ Other EIC activities

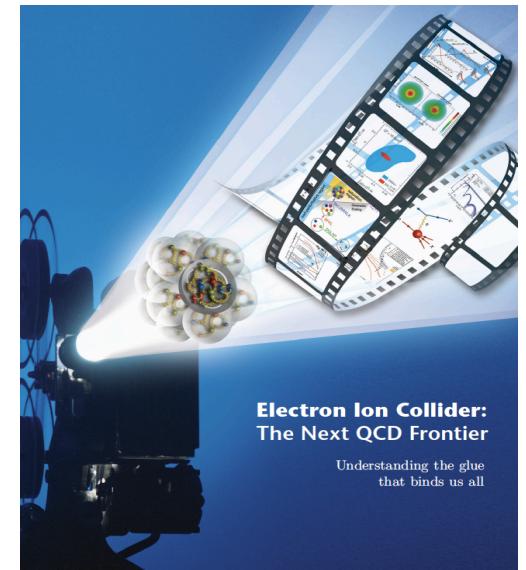
Close collaboration with BNL EIC task force

Qiu and Stratmann completed LDRDs exploring aspects of EIC science

Schenke's Early Career Award has major component on e+A physics

New post-doc Sievert hired on EIC BSA program development funds; active EIC visitor program

Venugopalan co-organizes annual POETIC series of conferences-POETIC VI in Paris (Sept 7-11); Qiu co-organized the EIC user meeting, Stony Brook, in June 2014



## **Students mentored: 2010-present**

**Hong Zhang, Tyler Corbett, P. Tribedy, M. Van der Klundert,  
S. Schlichting, M. Grahl, E. Seel, T. Epelbaum, F. Loshaj,  
R. K. Pokhorei, F. Rennecke, A. Mazeliauskas, Yue Wang, Mark Mace,  
Yuji Hirono, Masaru Hongo, Yuya Tanizaki, Shoichiro Tsutsui**

**Supervised by D. Kharzeev, R. Pisarski, J. Qiu, R. Venugopalan**

**D. Kharzeev: Joint faculty position at Stony Brook**

**J. Qiu: Adjunct Professor at Stony Brook (Brookhaven Professor at YITP)**

**R. Venugopalan: Adjunct Professor at Stony Brook**